11:37:04 OCA PAD AMENDMENT - PROJECT HEADER INFORMATION 10/18/93

Active

Project #: E-25-M26 Cost share #: N/A Rev #: 17
Center # : R6366-0A0 Center shr #: OCA file #:
Work type : RES
Contract#: BCS-8657691 Mod #: ADM REVISION Document : GRANT
Prime #: Contract entity: GTRC

Subprojects ? : Y CFDA: 47.041
Main project #: PE #: N/A

Project unit: MECH ENGR Unit code: 02.010.126
Project director(s):
KU D N MECH ENGR (404)894-6827

Sponsor/division names: NATL SCIENCE FOUNDATION / GENERAL
Sponsor/division codes: 107 / 000

Award period: 870801 to 940131 (performance) 940430 (reports)

Sponsor amount	New this change	Total to date
Contract value	0.00	334,000.00
Funded	0.00	334,000.00
Cost sharing amount		290.00

Does subcontracting plan apply ?: N

Title: FLOW VISUALIZATION BY MAGNETIC RESONANCE IMAGING

PROJECT ADMINISTRATION DATA

OCA contact: Jacquelyn L. Tyndall 894-4820

Sponsor technical contact

KAREN M. MUDRY
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6ATIONAL SCIENCE FOUNDATION
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ANDREA R. KLINE
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NATIONAL SCIENCE FOUNDATION
DGC/ENG
WASHINGTON, DC 20550

Security class (U,C,S,TS) : U ONR resident rep. is ACO (Y/N): N
Defense priority rating : N/A NSF supplemental sheet
Equipment title vests with: Sponsor GIT X
SONY VO 5800 U-MATIC VIDEO RECORDER.
Administrative comments -
ISSUED TO ADD DELIVERABLE CODE TO ITEM 1 OF DELIVERABLE SCHEDULE. CODE WAS ERRONEOUSLY LEFT OUT.

GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION

NOTICE OF PROJECT CLOSEOUT (SUBPROJECTS)

Closeout Notice Date 05/04/94

Project No. E-25-M26 Center No. R6366-0A0

Project Director KU D N School/Lab MECH ENGR

Sponsor NATL SCIENCE FOUNDATION/GENERAL

Project # E-25-X91 PD KU D N Unit 02.010.126 T
GRANT # BCS-8657691 MOD# BR DTD 9-22-93 MECH ENGR *
Ctr # 10/24-6-R6366-0A1 Main proj # E-25-M26 OCA CO JLT
Sponsor-NATL SCIENCE FOUNDAT /GENERAL 107/000
FLOW VISUALIZATION B
Start 870801 End 940131 Funded 10,000.00 Contract 10,000.00

LEGEND
1. * indicates the project is a subproject.
2. I indicates the project is active and being updated.
3. A indicates the project is currently active.
4. T indicates the project has been terminated.
5. R indicates a terminated project that is being modified.

NSF PYIA - David N. Ku, MD, PhD
Annual Progress Report

DYNAMIC MAGNETIC RESONANCE IMAGING OF BLOOD FLOW

David N. Ku, MD, PhD

MRI angiography has some serious problems that must be resolved before it is to become a clinically useful tool. First of all, there is poor resolution. In general, the resolution is adequate for a limited number of studies, but is not adequate for routine clinical use. The second problem is that with image dropouts. In any given patient a region of interest may show a complete blackout or a complete whiteout due to unknown causes. This produces havoc with the interpretation. And thirdly, there is no experimental basis for the interpretation of blood flow through arteries based on real images. One does not know whether swirling flow patterns or darkness truly indicates high blood flows or low blood flows or disturbed blood flows.

We began our investigations with MRI images of the abdominal aorta in order to better define the problems faced by the clinician in interpreting MRI and angiography. However, images of blood vessels quickly become confusing in that blood can appear white under some circumstances and black in others. Thus, it quickly became clear to us that although swirling patterns could be seen and make very nice movie pictures, especially for advertising agencies and PR work, that these were insufficient studies for good clinical evaluation. In order to increase our sensitivity and specificity on this test, we felt that it was important to study reproducible models.

Our approach has been to take phantoms or flow models from the laboratory that we could understand in a strict fluid mechanics sense and subject these models to MRI angiography. Models which we chose are simple models that could be easily analyzed but would give us essentially all the inherent features that would be important to clinical disease. These included straight tubes with Reynolds numbers ranging from the purely laminar range to the fully turbulent range, stenosis of approximately 75% by diameter with which we could generate turbulence and jets as well as separation regions, and aneurysms to simulate the conditions that would occur in such clinical disease.

Each one of these models proved to be quite informative in understanding MRI angiography. Our work so far has shown that the MRI has excellent resolution with the models being $\pm$ .5 mm. This is approximately the same resolution as can be shown with angiograms. However, when in vivo arteries are visualized, the resolution is not nearly as good, approximately $\pm$ 2 mm. Thus, the present resolution of MRI may be sufficient for great vessels and aneurysms. However, the anatomic resolution is insufficient for stenotic disease, especially of the lower limbs and the carotid. In addition, analysis of the flow patterns by comparing reproducible models to MRI images can be invaluable in quantifying stenosis and quantifying the amount of blood flow through these vessels. The development of MRI to visualize flow has great commercial potential as an alternative to costly and dangerous traditional angiography.

NSF PYIA - David N. Ku, MD, PhD

Statement of Residual Funds

The amount of unobligated funds expected to remain at the end of the period of current NSF support (1/31/89) is expected to be less than 10%.

NSF PYIA Annual Progress Report - 9/1989

Potential Value of Magnetic Resonance Angiography in Patients with Vascular Disease

David N. Ku, PhD, MD

Magnetic Resonance Imaging (MRI) is rapidly becoming an important tool in the evaluation of cardiovascular diseases. Already, MRI is the preferred modality for the diagnosis of cardiac septal defects and congenital abnormalities. The usefulness of MRI in peripheral vascular diseases stem from its ability to detect blood flow in superficial, deep, and intracranial vessels without intra-arterial injections and ionizing radiation. MRI can be used to produce anatomic images of the vessel lumen and wall as well as to obtain physiological information on flow rates and disturbances.

Imaging. A variety of techniques have been described to produce an angiographic type image on photographic film, each with its own advantages and disadvantages. Several technical artifacts can produce erroneous results. Vessel curvature in and out of the plane of imaging can produce the exact appearance of a local, fusiform stenosis. Poor signal levels from low flow or from small vessels may preclude the visualization of important collateral arteries. Present generation MR scanners have spatial resolution limitations which are typically worse than digital radiographic instruments. Most importantly, turbulent flowing blood can produce areas of signal loss or dropout which may not be representative of lumenal area. Our approach has been to develop an accurate projection image and to reconstruct a three-dimensional representation using back-projection modelling. An alternative approach is to take many tomographic images of a vessel along the transverse plane and reconstruct a three-dimensional view. Both techniques will be rigorously tested against a laboratory phantom or against traditional angiography. The future of these MR imaging will lay in the understanding of the blackout mechanism of flow and in more sophisticated reconstruction algorithms using artificial intellegence.

Velocimetry. Magnetic resonance can also be used to obtain flow rates and quantitative measurements of velocity in the complex three-dimensional flow field of hemodynamics in vivo. One method is to use time-of-flight to detect the movement of protons quantitatively. A second method is to use gradient echo sequences and analyze the phase images instead of the normally used magnitude images. The phase images can be set up to be directly proportional to local velocity. Velocity can be measured on a point-by-point basis in three directions to yield the pulsatile flow character within the vessel. In collaboration with Philips Medical Imaging, we are quantifying the precision and accuracy of these meaurements. The accuracy of these measurements is currently being determined through the use of flow phantoms designed to reproduce complex three-dimensional, unsteady hemodynamics. Verification of MR studies through comparisons with accepted modalities such as laser and ultrasound Doppler velocimetry should quantify the accuracy of these studies. Future investigations will utilize the MR velocity measurements to quantitatively determine mean and phasic flow rates and pressure drops through a stenosis.

Discussion. The ultimate diagnostic modality for vascular diseases will include an anatomic image as well as physiologic information of blood flow. With careful and judicious development, MR imaging may provide a simultaneous display of this information through a test which is accurate, non-invasive, has low risk, and is not prohibitively expensive.

Georgia Tech

THE GEORGE W. WOODRUFF SCHOOL OF
MECHANICAL ENGINEERING

David N. Ku, MD, PhD
Associate Professor
(404) 894-6827
(404) 894-2291 Fax
DKU@GTRI01.BITNET

Georgia Institute of Technology
Atlanta, Georgia 30332-0405

October 15, 1990

Dr. Peter Katona
Bioengineering
Room 1134
National Science Foundation
1800 G Street, NW
Washington, DC 20550

Re: NSF EET-8657691

Dear Dr. Katona:

Enclosed is my annual report for the Presidential Young Investigator Award for base year 4.

I will be moving to M.I.T. in the next few months and would like to move my remaining NSF PYIA funds to Cambridge. Please let me know what NSF requires for the official transfer of funds.

Thank you.

Sincerely,

David N. Ku, MD, PhD
Associate Professor of Mechanical
Engineering and Surgery

DNK:sek

Enclosures

NSF PYIA Annual Progress Report - 9/1990
David N. Ku, MD, PhD

During the past year, I have used PYIA funds to continue progress in the area of Magnetic Resonance Imaging, complete the analysis and reporting of the biomechanics of swallowing, and expand into a new area of mechanical determinants of end-stage vascular disease.

Magnetic Resonance Imaging (MRI): A method of three-dimensional computer modelling of multi-planar projection images has been developed for MR angiography. The model can be visualized and manipulated interactively by the physician to determine better views of lesions and ascertain optimal surgical approaches. This work was reported at two meetings at the end of 1989 and a manuscript is in preparation.

The signal losses which have been observed in previous MR images have been reproduced and quantified in phantom models of stenoses. The signal loss is a function of stenosis shape and Reynolds number. The underlying cause of the signal loss has been determined to arise from local and convective acceleration of the fluid. This fluid acceleration effect can be predicted quantified using basic. To date, the effect has been quantified with good agreement between prediction and measurment. The signal losses from turbulent flow can be explained using this theory. Preliminary results have been presented at the Society for Magnetic Resonance in Medicine annual meeting and a manuscript is in preparation.

MR velocimetry is possible using a phase-velocity encoding technique. Extensive validation studies have been performed to quantify the precision and accuracy of this technique for complex, three-dimensional fluid motion. This work was presented at the Society for Magnetic Resonance Imaging and the World Congress on Biomechanics. The article is to appear in the November issue of Journal of Biomechanical Engineering.

Our work on the biomechanics of oro-pharyngeal swallowing is to appear in the next issue of Annals of Bioengineering. This research has identified the timing of the driving forces behind the swallowing of liquids with important new implications to the diagnosis and treatment of dysphagia.

We have begun work on the collapse of stenotic arteries due to decreases in intralumenal pressure. Mechanical forces in end-stage vascular disease may lead to plaque rupture and sudden changes in flow rate. This work involves both experimental and computational fluid dynamics which has been presented at several international meetings. The computational aspect is to appear in the Journal of Biomechanical Engineering. Additional funding is being sought from the American Heart Association.

E25-M26
4

Georgia Tech

THE GEORGE W. WOODRUFF SCHOOL OF
MECHANICAL ENGINEERING

David N. Ku, MD, PhD
Associate Professor
Woodruff Faculty Fellow

Georgia Institute of Technology
Atlanta, Georgia 30332-0405

October 30, 1991

Dr. Peter Katona
Bioengineering, Room 1134
National Science Foundation
1800 G Street, NW
Washington, DC 20550

RE: NSF BCS-8657691

Dear Peter,

Enclosed is the annual report and a request for matching funds for base year 5 as well. Eligible matching funds have been obtained from the Whitaker Foundation, a private, non-profit foundation.

As you know, I am no longer moving to MIT as I have decided to stay at Georgia Tech. Thank you for your support. I wish you the best in your new position at the Whitaker Foundation.

Sincerely,

David N. Ku, MD,PhD
Associate Professor of Mechanical
Engineering and Surgery

DNK:mjk
Enclosure

CONCURRENCE:

David B. Bridges
Contracting Officer
Office of Contract Administration

NSF PYIA Annual Progress Report, 10/1991
David N. Ku, MD, PhD

During the past year I have used PYIA funds to continue progress in several areas including magnetic resonance velocimetry, and the biomechanics of compliant stenoses.

We have presented the results of our work to the 1991 Annual Meeting of the Society for Magnetic Resonance Imaging in which we report the accuracy of MR-phase velocity mapping in straight tubes and stenoses. The MR velocity measurements demonstrated that phase velocity mapping is precise and accurate for simple, laminar flow but that significant errors arise from turbulent and accelerating flows. In the presence of turbulent fluctuations, MR measurements were adequate for total flow or average velocity measurement but not for velocity on a pixel-by-pixel basis. Later on this year we reported further results to the Annual Meeting of the Society of Magnetic Resonance in Medicine. In this paper we discuss the problems of convective acceleration in the convergent section of the stenosis which cause the measured values of velocity to deviate by as much as 40% from the theoretical values. These results suggest that acceleration may be the specific mechanism for the problems encountered when measuring turbulent flow. The phase incoherence seen when measuring flow with high turbulence intensity could be due to the inherent high levels of random temporal and spatial accelerations found in turbulence.

At the World Congress on Medical Physics and Biomedical Engineering in Kyoto, Japan, we submitted several invited papers. One involved the choking of viscous one-dimensional collapsible tube flow through a stenotic artery. Using a one-dimensional solution for flow through a short stenotic tube solved by the unsteady McCormick predicter-correcter finite different scheme, we were able to evaluate the contribution of laminar and turbulent friction to flow in these compliant stenoses. The findings indicate that flow choking can substantially contribute to the hemodynamics of diseased arteries and may contribute to the dynamic variable resistances previously measured by cardiac physiologists.

The collapse of stenoses may contribute to the rupture of atheroscleratic plaque with subsequent embolism and thrombosis. It is possible that fracture of the fibrous cap of atherosclerotic plaques can be precipitated by mechanical fatigue. We have since tested human arteries with plaques in a high-frequency, high-load, accelerated fatigue apparatus capable of loading specimen intention or bending. After 500,000 cycles, our preliminary results indicate loss of ultimate strength after cyclic bending and scanning electron microscopy defects in the media and plaque cap after cyclic bending. These results were statistically significant with $p < 0.02$. This information concerning damage accumulation in normal and diseased arteries provides a better understanding of the mechanism of

plaque rupture and may lead to strategies of prediction and prevention of catastrophic heart attacks and strokes.

Part of our effort this year was towards the submission and publication of prior results. One article entitled "Accuracy of Velocity and Shear Rate Measurements Using Pulsatile Ultrasound" was accepted for publication in Ultrasound in Medicine and Biology. Another analysis of "Collapse of Diseased Arteries with Eccentric Cross-Section" was accepted for publication by the Journal of Biomechanics. All of the above work carried acknowledgement of support by the National Science Foundation.

E-25-M26 5,6 E-25-M26 5,6

OMB Number 345-0058

NATIONAL SCIENCE FOUNDATION
1800 G STREET, NW
WASHINGTON, DC 20550

BULK RATE
POSTAGE & FEES PAID
National Science Foundation
Permit No. G-69

PI/PD Name and Address

David N. Ku
Mechanical Engineering
GA Tech Res Corp - GIT
Atlanta GA 30332

NATIONAL SCIENCE FOUNDATION
FINAL PROJECT REPORT

PART I - PROJECT IDENTIFICATION INFORMATION

1. Program Official/Org. John D. Enderle - BCS

2. Program Name BIOENGINEERING & AIDING THE DISABLED PRO

3. Award Dates (MM/YY) From: 08/87 To: 01/94

4. Institution and Address

GA Tech Res Corp - GIT
Administration Building
Atlanta GA 30332

5. Award Number 8657691

6. Project Title

Presidential Young Investigator Award

This Packet Contains
NSF Form 98A
And 1 Return Envelope

NSF Grant Conditions (Article 17, GC-1, and Article 9, FDP-11) require submission of a Final Project Report (NSF Form 98A) to the NSF program officer no later than 90 days alter the expiration of the award. Final Project Reports for expired awards must be received before new awards can be made (NSF Grants Policy Manual Section 677).

Below, or on a separate page attached to this form, provide a summary of the completed projects and technical information. Be sure to include your name and award number on each separate page. See below for more instructions.

PART II - SUMMARY OF COMPLETED PROJECT (for public use)

The summary (about 200 words) must be self-contained and intelligible to a scientifically literate reader. Without restating the project title, it should begin with a topic sentence stating the project's major thesis. The summary should include, if pertinent to the project being described, the following items:

- The primary objectives and scope of the project
- The techniques or approaches used only to the degree necessary for comprehension
- The findings and implications stated as concisely and informatively as possible

See attached sheets

PART III - TECHNICAL INFORMATION (for program management use)

List references to publications resulting from this award and briefly describe primary data, samples, physical collections, inventions, software, etc. created or gathered in the course of the research and, if appropriate, how they are being made available to the research community. Provide the NSF Invention Disclosure number for any invention.

I certify to the best of my knowledge (1) the statements herein (excluding scientific hypotheses and scientific opinion) are true and complete, and (2) the text and graphics in this report as well as any accompanying publications or other documents, unless otherwise indicated, are the original work of the signatories or of individuals working under their supervision. I understand that willfully making a false statement or concealing a material fact in this report or any other communication submitted to NSF is a criminal offense (U.S. Code, Title 18, Section 1001).

[signature]	4/1/94
Principal Investigator/Project Director Signature	**Date**

IMPORTANT:
MAILING INSTRUCTIONS
Return this *entire* packet plus all attachments in the envelope attached to the back of this form. Please copy the information from Part I, Block I to the *Attention block* on the envelope.

Part II - Summary of Completed Project

The project proposed in the initial application for the PYIA was to develop the fluid mechanical validity of Magnetic Resonance image and measure blood flow in the human body.

The objective of the Presidential Young Investigator Award is to provide the beginning scientist with funds to establish an active environment for productive research. For me, this Award had an enormous impact. The award has allowed me the freedom to establish three new areas of research in bioengineering which would not have been possible without these discretionary funds. These areas are distinctly different from any previous research performed by myself and represent the blossoming of new areas for bioengineering research.

In 1987, MRI was fairly new and only sporadic papers on imaging of blood flow were available. Now, all the major journals in MR regularly publish papers in this area. We have been one of the primary laboratories to quantitatively document the accuracy of MR velocimetry measurements in comparison with established velocimeters such as laser Doppler anemometry and ultrasound Doppler. MR velocity measurements have been made for accurate hemodynamic phantoms and directly compared with in vivo measurements. This technique has now been developed to the point where the traditional fluid mechanics community is beginning to use this instrument for traditional fluid dynamic studies. As such, the development of this technique represents one of the first technology transfers from medicine to engineering instead of the other way around. We have demonstrated the validity of MR angiography for normal and aneurysmal vessels, but its failings with stenotic disease. We have further defined the role of turbulence, convective acceleration, and vibrations on signal loss patterns in MR angiograms. A strong collaboration with the Emory University Department of Radiology and Philips Medical Imaging Corp. has been established. Numerous presentations and papers have been published in both bioengineering and magnetic resonance journals (attached list). Three undergraduate and three graduate students were supported in this effort, producing two Masters theses and two PhD theses.

In addition to the above, the availability of the PYI award made possible new projects in studying flow through collapsible stenoses and swallowing. Highly diseased arteries in the human cause heart attacks and strokes. The clinical catastrophes usually occur because the plaque breaks and exudes fat into the blood stream causing blockage for blood flow. We have developed a new hypothesis which explains this breakdown in terms of the collapsing plaque in highly stenotic arteries. A stenosis is a constriction from atherosclerosis. This constriction produces an unusual hemodynamic low pressure zone in the throat of the stenosis. The plaque then becomes loaded in

compression instead of tension and may buckle. The cyclic loading of alternating tension and compression can weaken the plaque cap producing a fatigue fracture of the surface. This new project has mathematically predicted the region of collapse using one-dimensional fluid mechanics, predicted the shapes of buckling for the thick walled, eccentric plaque, and demonstrated the fracture of the plaque cap in human arteries under compression loading. The fields of fracture mechanics and fluid mechanics have been integrated to provide the most compelling explanation of strokes and heart attacks to date. Two Masters theses and two PhD theses have been generated in this area.

A third project has defined the complicated events of oro-pharyngeal swallowing as amenable to biomechanical analysis. The normal physiology of swallowing requires analysis of the movement in LaGrangian terms along with the treatment of the bolus as a fluid or a semi-solid subjected to unsteady forces. Our article represents the one of the first such engineering analyses of swallowing in the literature. This project has led in part to an RFA from the National Institute on Aging to study to mechanics of swallowing in the aged. A Masters thesis was written in this subject.

The findings of the research funded by the PYIA are extensive. Magnetic Resonance Imaging is now an important tool in the diagnosis of cardiovascular disease. Our work has contributed to the validation and development of this instrument for clinical diagnosis. A new mechanism for heart attacks and strokes has been described through our fluid and solid mechanical analysis of flows through collapsible stenoses. And our quantitative description of the physiology of swallowing will allow physicians to better diagnosis swallowing disorders and possible surgical cures for these disorders.

I thank the National Science Foundation for the opportunity to be creative and grow.

Part III - Technical Information

See list of references attached. The primary data in the MR project consisted of making measurements on a Philips Whole Body Scanner. For the collapsible stenosis project, computational fluid mechanics was developed, experimental models of collapsible stenoses were created, and human arteries were subjected to cyclic loading conditions. Measurements of human swallowing using manofluorometry were used to draw conclusions regarding swallowing.

PUBLISHED BOOKS AND PARTS OF BOOKS

1. Glagov, S., Bassiouny, H., Masawa, N., Ku, D.N., Vito, R.P. Giddens, D.P., Zarins, C.K. "Hemodynamic and structural determinants of human plaque stability," in Atherosclerosis VIII, (G. Crepaldi et al, eds) Amsterdam, Elsevier Science Publ pp. 411-415, 1989.

2. Ku, D.N., Zeigler M., Stewart, M., "A study of predicted and experimental wall collapse in models of highly stenotic arteries." 2nd International Symposium on Biofluid Mechanics,(D. Liepsch, ed) Munich, Karger Scientific Publ., pp. 409-416, 1989.

3. Poiseau, E., Yoganathan, A., Ku, D.N., Dixon, T., "Magnetic resonance imaging of cardiac blood flow: An in vitro study." 2nd International Symposium on Biofluid Mechanics, (D. Liepsch, ed) Munich, Karger Scientific Publ., pp. 241-248, 1989.

4. Ku, D.N., Peifer, J., Biancheri, C., Pettigrew, R.I., Engels, H. "Potential Value of Magnetic Resonance Angiography in Patients with Vascular Disease", Current Critical Problems in Vascular Surgery (F.J. Veith, ed), Vol. II, pp. 36-41, 1990.

PUBLISHED JOURNAL PAPERS (REFEREED)

1. Ku, D.N., Ma, P.P., McConnel, F.M.S. Cerenko, D., "Frame by frame analysis of swallowing using manofluorography," Surgical Forum, vol. 39, pp. 545-548, 1988.

2. Binns, R.L., Ku, D.N., "The effect of stenosis on wall motion: A possible mechanism of stroke and transient ischemic attack." Arteriosclerosis, Vol. 9, pp. 842-847, 1989.

3. Ku, D.N., Zeigler, M.N., Downing, J.M., "One-dimensional steady inviscid flow through a stenotic collapsible tube," J. Biomechanical Engineering, Vol. 112, pp. 444-450, 1990.

4. Ku, D.N., Biancheri, C., Peifer, J., Markou, C., Engels, H., Pettigrew, R.I., "An evaluation of magnetic resonance velocimetry for steady flow", Journal of Biomechanical Engineering, Vol. 112, pp.464-472, 1990.

5. Ku, D.N., Ma, P.P., McConnel, F.M.S., Cerenko, D., "A kinematic study of oropharyngeal swallowing of a liquid," Annals of Biomedical Engineering, pp. 655-669, 1990.

6. McKinsey, J., McCord, B.N., Aoki, T., Ku, D.N. "Can mechanical stress cause fatigue of the atherosclerotic plaque"? Surgical Forum, Vol 42: pp.318-19, 1991.

7. Oshinski, J.N., Ku, D.N., Bohning, D.E., Pettigrew, R.I. "The effects of acceleration on the accuracy of MR phase velocity measurements, Journal of Magnetic Resonance Imaging, Vol. 2, pp 665-670, November/December 1992.

8. Aoki, T., Ku, D.N. "Collapse of diseased arteries with eccentric cross-section," Journal of Biomechanics, Vol. 26:2, pp 133-42, 1993.

9. Peifer, J.W., Ku, D.N., "Computer modelling of the abdominal aorta using magnetic-resonance images," Annals of Biomedical Engineering, Vol. 21:2, pp 237-46, 1993.

10. Moore, J.E., Ku, D.N. "Pulsatile velocity measurements in a model of the human abdominal aorta under resting conditions," Journal of Biomechanical Engineering, in press.

11. Moore, J.E., Ku, D.N. "Pulsatile velocity measurements in a model of the human abdominal aorta under simulated exercise and postprandial conditions," Journal of Biomechanical Engineering, in press.

12. Moore, J.E., Maier, S.E., Ku, D.N., Boesiger, P. "Hemodynamics in the abdominal aorta: A comparison of in vitro and in vivo measurements." Journal of Applied Physiology, in press.

CONFERENCE PRESENTATIONS WITH PROCEEDINGS (REFEREED)

1. Ku, D.N., McConnel, F., Cerenko, D., "Quantitative assessment of the fluid dynamics of phyaryngeal blood transport," 3rd National Conference of Biomedical Engineering, China, p. 12, 1987.

2. Ku, D.N., Pettigrew, R.I., Elgendy Y., "Dynamic magnetic resonance angiography," Southern Association of Vascular Surgery, p. 74, 1988.

3. Binns, R.L., Ku, D.N., "The effect of stenosis on wall oscillation in an "ideal" latex collapsible tube model: A possible mechanism of stroke and transient ischemic attack," The Society for Vascular Surgery, Chicago, p. 40, 1988.

4. Ku, D.N., Ma, P.P., McConnel, F.M.S., Cerenko, D., "Frame by frame analysis of swallowing using manofluorography," American College of Surgeons 74th Clinical Congress, Chicago, 1988.

5. Ku, D.N., Elgendy, Y., Pettigrew, R.I., "Magnitude magnetic resonance imaging of a stenosis," World Congress on Medical Physics and Biomedical Engineering, San Antonio, p. 377, 1988.

6. Ku, D.N. and Binns, R., "Systolic and diastolic wall collapse from high grade stenoses". Scientific Conference on Coronary Atherosclerosis and Thrombosis, 1989.

7. Biancheri, C., Ku, D.N., Yoganathan, A., Dixon, T., Pettigrew, R., "Effect of stenosis geometry on magnitude magnetic resonance imaging," 1989 Joint ASCE/ASME Biomechanics Symposium, p. 13-16.

8. Ma, P.P., Ku, D.N., Cerenko, C., McConnel, F.M.S., "Quantitative manofluorography for the evaluation of normal pharyngeal swallowing." 1989 Joint ASCE/ASME Biomechanics Symposium, p. 17-20.

9. Ku, D.N., Zeigler M., Stewart, M., "A study of predicted and experimental wall collapse in models of highly stenotic arteries." 2nd International Symposium on Biofluid Mechanics, Munich, p. 567-580, 1989.

10. Poiseau, E., Yoganathan, A., Ku, D.N., Dixon, T., "Magnetic resonance imaging of cardiac blood flow: An in vitro study." 2nd International Symposium on Biofluid Mechanics, Munich, p. 345-357, 1989.

11. Ku, D.N., "Potential value of magnetic resonance angiography in patients with vascular disease," Sixteenth Annual Symposium on Current Critical Problems and New Horizons in Vascular Surgery, New York, 1989.

12. Peifer, J.W., Ku, D.N., "Three-dimensional modelling of the abdominal aorta based on magnetic resonance images." Cardiovascular Science and Technology: Basic and Applied. Louisville, KY, 1989.

13. Ku, D.N., Biancheri, C., Peifer, J., "Quantitative measurements of stenotic flows using magnetic resonance imaging". ASME WAM, 1989 Advances in Bioengineering, BED - Vol. 15, p. 9-10.

14. Ku, D.N., Zeigler, M.N., "Effects of stiffness on wall collapse within a stenosis." ASME, WAM, 1989 Advances in Bioengineering, BED - Vol. 15, p. 141-142.

15. Oshinski, J., Biancheri, C., Ku, D.N., Markou, C., Pettigrew, R., Engels, H. "Phase velocity encoding of laminar and turbulent flow in a smooth stenosis and curved tube." Society for Magnetic Resonance Imaging, 8th Annual Meeting, Washington, D.C., p. 15, 1990.

16. Peifer, J., Ku, D.N., Engels, H., Pettigrew, R., "Three-dimensional modeling of an abdominal aorta phantom from two MR images." Society for Magnetic Resonance Imaging, 8th Annual Meeting, Washington, D.C. 1990.

17. Ku, D.N., Pettigrew, R.I., Markou, C., Biancheri, C., "Fluid mechanical mechanisms of signal loss in MR images of flow through smooth and sharp stenoses," Society of Magnetic Resonance in Medicine, New York, 1990, Vol. 1, p. 226.

18. Ku, D.N., Markou, C., Oshinski, J., "Magnetic resonance imaging phase-velocity encoding measurements of secondary and separated flows." First World Congress of Biomechanics, San Diego, 1990, II-126.

19. Moore, J.E., Ku, D.N., "Initial flow velocimetry in a model of the human abdominal aorta." First World Congress of Biomechanics, San Diego, 1990, II-186.

20. Oshinski, J.N., Ku, D.N., Markou, C.P., Pettigrew, R.I., "Evaluation of the accuracy of MR phase-velocity imaging in straight tubes and stenosis," Journal of Magnetic Resonance Imaging, Vol. 1, p. 217, 1991.

21. Ku, D.N., Oshinski, J.N., Markou, C.P., Pettigrew, R.I. "Some errors in magnetic resonance flow measurements resulting from fluid dynamics, ASME Biomechanics Symposium, pp 41-44, 1991.

22. McCord, B., Aoki, T., Ku,D.N., "Does cyclic stress cause fatigue of the atherosclerotic plaque?" World Congress on Medical Physics and Biomedical Engineering, Kyoto, Japan, p. 268, 1991.

23. Downing, J.M., Ku, D.N., "The choking of viscous one-dimensional collapsible tube flow through a stenotic artery." World Congress on Medical Physics and Biomedical Engineering, Kyoto, Japan, p. 253, 1991.

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PART IV -- FINAL PROJECT REPORT -- SUMMARY DATA ON PROJECT PERSONNEL

(To be submitted to cognizant Program Officer upon completion of project)

The data requested below are important for the development of a statistical profile on the personnel supported by Federal grants. The information on this part is solicited in resonse to Public Law 99-383 and 42 USC 1885C. All information provided will be treated as confidential and will be safeguarded in accordance with the provisions of the Privacy Act of 1974. You should submit a single copy of this part with each final project report. However, submission of the requested information is not mandatory and is not a precondition of future award(s). Check the "Decline to Provide Information" box below if you do not wish to provide the nformation.

Please enter the numbers of individuals supported under this grant.
Do not enter information for individuals working less than 40 hours in any calendar year.

	Senior Staff		Post-Doctorals		Graduate Students		Under-Graduates		Other Participants[1]	
	Male	Fem.	Male	Fem.	Male	Fem.	Male	Fem.	Male	Fem.
A. Total, U.S. Citizens	2				6	2	1	3		1
B. Total, Permanent Residents										
U.S. Citizens or Permanent Residents[2]:										
American Indian or Alaskan Native										
Asian.....										
Black, Not of Hispanic Origin.....										
Hispanic										
Pacific Islander										
White, Not of Hispanic Origin										
C. Total, Other Non-U.S. Citizens										
Specify Country										
1. China					1	1				
2. Greece			1							
3. Egypt					1					
D. Total, All participants (A + B + C)	2		1		8	3	1	3		1
Disabled[3]										

☐ Decline to Provide Information: Check box if you do not wish to provide this information (you are still required to return this page along with Parts I-III).

[1] Category includes, for example, college and precollege teachers, conference and workshop participants.

[2] Use the category that best describes the ethnic/racial status fo all U.S. Citizens and Non-citizens with Permanent Residency. *(If more than one category applies, use the one category that most closely reflects the person's recognition in the community.)*

[3] A person having a physical or mental impairment that substantially limits one or more major life activities; who has a record of such impairment; or who is regarded as having such impairment. *(Disabled individuals also should be counted under the appropriate ethnic/racial group unless they are classified as "Other Non-U.S. Citizens.")*

AMERICAN INDIAN OR ALASKAN NATIVE: A person having origins in any of the original peoples of North America and who maintains cultural identification through tribal affiliation or community recognition.

ASIAN: A person having origins in any of the original peoples of East Asia, Southeast Asia or the Indian subcontinent. This area includes, for example, China, India, Indonesia, Japan, Korea and Vietnam.

BLACK, NOT OF HISPANIC ORIGIN: A person having origins in any of the black racial groups of Africa.

HISPANIC: A person of Mexican, Puerto Rican, Cuban, Central or South American or other Spanish culture or origin, regardless of race.

PACIFIC ISLANDER: A person having origins in any of the original peoples of Hawaii; the U.S. Pacific territories of Guam, American Samoa, and the Northern Marinas; the U.S. Trust Territory of Palau; the islands of Micronesia and Melanesia; or the Philippines.

WHITE, NOT OF HISPANIC ORIGIN: A person having origins in any of the original peoples of Europe, North Africa, or the Middle East.